

**HOT-FILM SYSTEM FOR TRANSITION DETECTION
IN CRYOGENIC WIND TUNNELS**

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INTRODUCTION TO HOT-FILM SYSTEMS FOR CRYOGENIC WIND TUNNELS

It is well known that the determination of the location of boundary-layer transition is necessary for the correct interpretation of aerodynamic data in transonic wind tunnels such as the U.S. National Transonic Facility (NTF) and the Langley 0.3-Meter Transonic Cryogenic Tunnel (0.3-m TCT) (refs. 5 and 22). In the past, hot-film gauges (hot films) have proved to be one of the best devices for detecting the beginning and end of boundary-layer transition on models in conventional (near-ambient temperature and pressure) wind tunnels (ref. 7). However, the types of hot films used in the conventional wind tunnels are unsuitable for use in cryogenic wind tunnels, such as the NTF, because of the large range of temperatures (cryogenic to ambient) and because of the high Reynolds numbers encountered in testing (refs. 8 and 9) (fig. 1). In addition, the wing of a typical NTF model of a transport aircraft, with a wing span of 4 to 5 feet, would require as many as 100 hot films to adequately locate transition over the wide range of test conditions encountered in a typical force and moment test. Furthermore, the hot films would have to be located on the surface of 3-D shapes such as leading edges of wings and winglets.

In the late 1970's the Douglas Aircraft Company (DAC) developed a vapor deposition hot-film system for transition detection in cryogenic wind tunnels (refs. 23 and 24). The ability of the DAC hot-film system to detect transition was first validated in an ambient temperature test (ref. 6) and later validated in a cryogenic test in the 0.3-m TCT (ref. 8). Although a significant amount of transition data was obtained with the DAC hot-film system in the 0.3-m TCT, the original goal of on-line detection of transition was not achieved. Since the tests in the TCT, Langley has developed an improved deposition technique for cryogenic hot films. The new technique includes a new dielectric and a new process for the buildup of the hot-film substrate. Tests of the new hot films in a low-speed tunnel demonstrated the ability to obtain on-line transition data with an enhanced simultaneous hot-film data acquisition system.

Langley is also developing a large-scale vapor deposition system which will include two large (5-foot diameter) chambers that will be used to put hot films on large NTF models.

- Special requirements
 - Operate from ambient to cryogenic condition
 - Nonintrusive (less than critical roughness height)
 - Large number of films and realistic models (i.e., 3-D shapes)
 - Obtain transition on line as adjunct to primary force and moment test
- A cryo hot film system was developed by Fancher of DAC
 - Validated system in ambient temperature and cryogenic tunnels
- Since validation tests, Langley has been developing:
 - A new hot film and substrate deposition technique
 - Two new on-line data acquisition systems
 - A system for transition detection of NTF models

Figure 1

MODEL USED IN CRYOGENIC TRANSITION DETECTION STUDY: 0.3-M TCT

The 2-D airfoil used in the boundary layer transition detection study in the 0.3-m TCT (ref. 8), with 38 hot films on the upper surface, is shown mounted between the two test section turntables (fig. 2). With a technique they had developed (refs. 6, 23, and 24), DAC vapor deposited the hot films and their respective 76 gold leads on a dielectric substrate that was uniformly applied to the entire flow surface of the airfoil. The surface installation of the vapor deposited hot films and gold leads was 4 to 8 microinches thick, well below the critical roughness height required to trip the thinnest adiabatic laminar boundary layer that was encountered during the tests.

The 9-inch chord model, made of beryllium copper, was an advanced-technology supercritical airfoil, designed by NASA, designated the NASA SC(3)-0712. The model was fabricated with 16 internal liquid nitrogen (LN_2) cooling passages and 7 thermocouples, 0.050 below the surface, to monitor the model wall temperature. The ability to cool the model to wall temperatures as low as $169^{\circ}R$ demonstrated the ability of the cryogenic hot-film system to operate at cryogenic conditions.

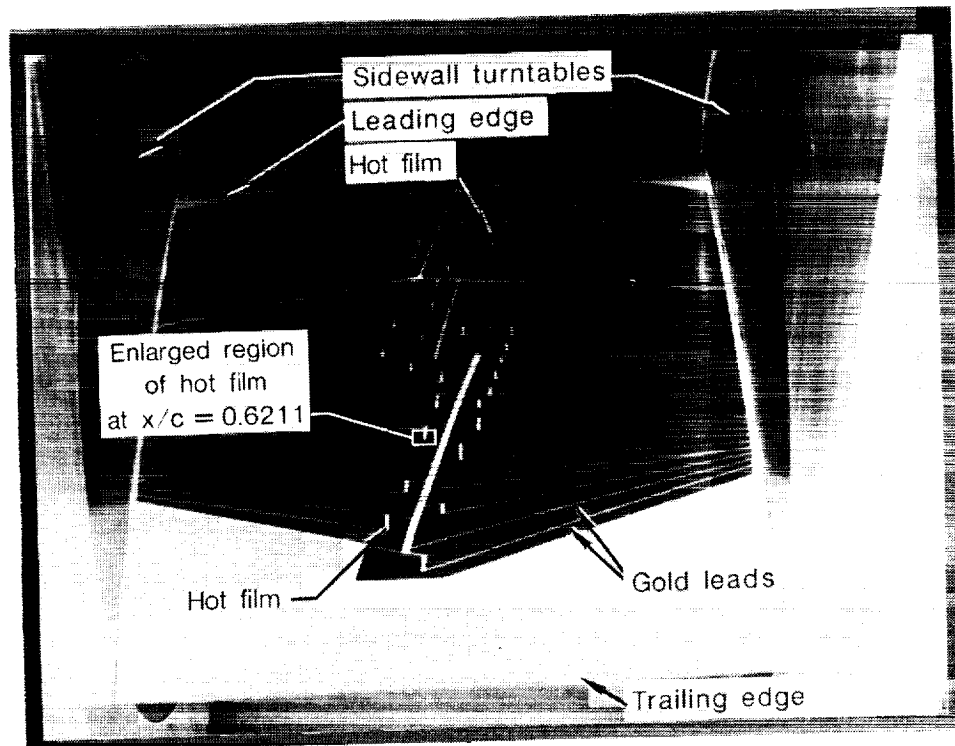


Figure 2

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ENLARGED VIEW OF HOT-FILM AND GOLD LEADS

The hot films, which are extremely small and barely visible in figure 2 can easily be distinguished in an enlarged photograph of the hot-film at an x/c of 0.6211 (fig. 3). The photograph, which has a magnification of about 12, clearly indicates the hot-film located between the two gold leads. The gold leads are so thin that a portion of the metallic hot films (i.e., the end pads) can be seen through the leads.

The DAC procedure used to deposit an array of specialized cryogenic hot films on the surface of a model (refs. 6, 23, and 24) consisted of first applying a coating of dielectric substrate on the model, in this case an epoxy paint, and then polishing the substrate to a smooth finish of a uniform thickness of about 0.001 in. (0.0254 mm). Next, a pattern of hot films was applied to the surface by a vapor deposition technique. Each end of the hot film was then connected to a copper wire contact (i.e., model surface penetration) by a set of vapor deposited gold leads.

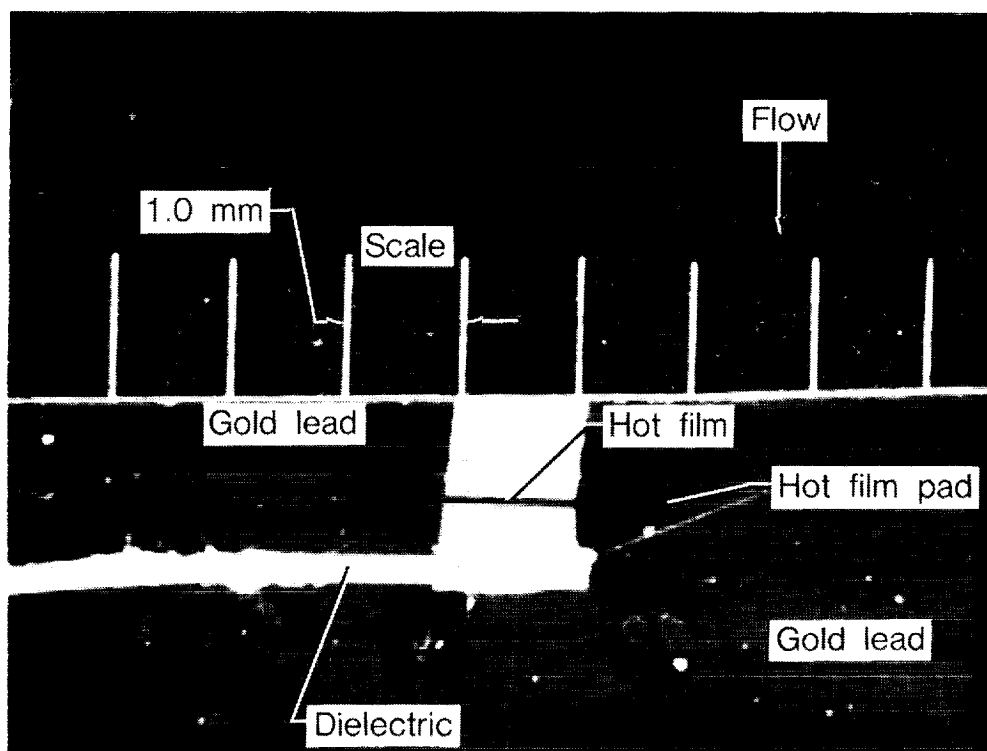


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ENLARGED VIEW OF WIRE PENETRATION CONTACT FOR HOT-FILM LEADS

An important component of the vapor deposited cryogenic hot-film system is the model wire penetrations which are flush to the model surface and serve to carry the hot-film signal from the vapor deposited electrical leads, through insulated wires in the model, to lead wires outside the model. For 2-D airfoils (refs. 6, 8, and 9), the wires run from the sides of the model at the point where the vapor deposited lead connects to the wire penetrations. This connection which is a vital link in the hot-film system must have a constant, low resistance electrical connection.

For the transition detection study in the 0.3-m TCT (ref. 8), the wire penetration was accomplished by cutting 76 slots (38 in each side) in the upper surface of the model and 20 slots in the lower surface to provide lead wires for 38 upper surface hot films and 10 lower surface hot films (fig. 4). The wire penetration contact points for the hot-film leads protrude above the surface of the airfoil about 0.001 in (0.0254 mm) in order to be flush with the surface dielectric coating, which is also about 0.001 in thick. The penetration wires were bonded into the slots with an electrically nonconducting epoxy. After the installation, each wire was checked to ensure that it was isolated from the model. (The 7 tubes on the side of the model (fig. 4) are part of the liquid nitrogen cooling system.)

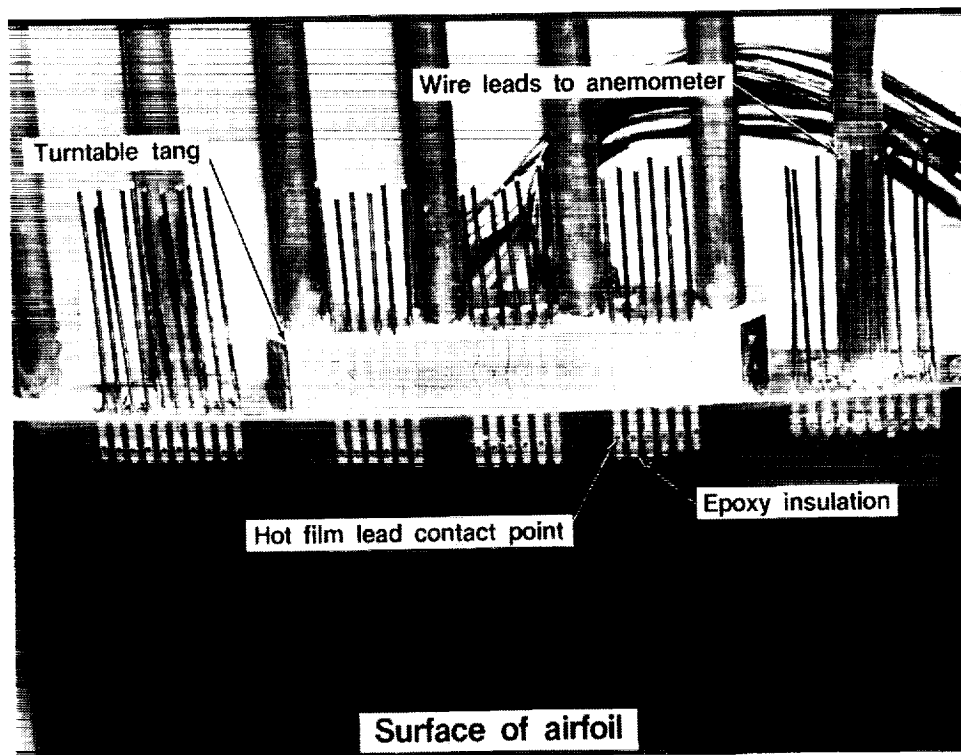


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INITIAL APPROACH TO METALIZATION FOR CRYOGENIC HOT-FILM SYSTEM

For a number of years prior to the hot-film tests in the 0.3-m TCT (refs. 8 and 9), Langley had been evaluating various dielectric substates that would be considerably thinner than the epoxy paint used in the DAC method and that could be applied by a vapor deposition process that would ensure a uniformly thick substrate over 3-D shapes. Finally, a vapor deposited polymer called Parylene C was selected as the potential dielectric for use on a 3-D model to be tested in the NTF. The initial approach was to coat a number of polished aluminum coupons (about 4 in by 4 in) with various thicknesses of Parylene C (about 0.001 in to 0.003 in) and then deposit a chrome/nickel metal coating over the Parylene. It appeared at first the approach of depositing Parylene C as a dielectric on a model surface and then depositing the hot films on top of the Parylene C in a manner similar to the DAC hot-film method (refs. 6, 8, 9, 26, and 27) would be a satisfactory technique for 3-D model hot-film application. However, when a metallic coupon with an array of hot films vapor deposited by this technique were checked for uniformity of resistance, it was discovered that there was a wide variation in the level of resistance. In addition, when these same films were powered with a moderately low level of current by an anemometer, there was a significant number of hot-film failures. When the metalization of a chrome/nickel strip deposited on top of a coating of Parylene C was examined under a microscope (ref. 9), a number of cracks were discovered in the metals (fig. 5). It was soon realized the reason for the cracks was due to the flexible nature of the Parylene C dielectric substrate. The Parylene C has the capability to accommodate different linear coefficients of expansion. However, when hot films, which have intrinsic stresses, were deposited on the Parylene surface, fractures resulted in the metal film (fig. 5).



Figure 5

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LANGLEY-DEVELOPED METALIZATION FOR CRYOGENIC HOT-FILM DEPOSITION

The problem of the fractures in the metalization procedure, indicated in figure 5, was solved after several months of intensive research and development. The solution to the fractures in the metalization was to coat the Parylene dielectric substrate with a thin layer of fused silica (SiO_2) (ref. 9). When this Langley-developed technique was examined in the microscope, there were no fractures (i.e., failures) in the metal film (fig. 6). This addition of the SiO_2 "buffer" layer enabled the Parylene C to act as a strain isolation pad between the model surface and the layer of SiO_2 . With the addition of a layer of SiO_2 , a dielectric substrate was produced that was thermally, chemically, and mechanically stable enough to prevent the cracking failure of the hot films at both ambient and cryogenic conditions (ref. 9).

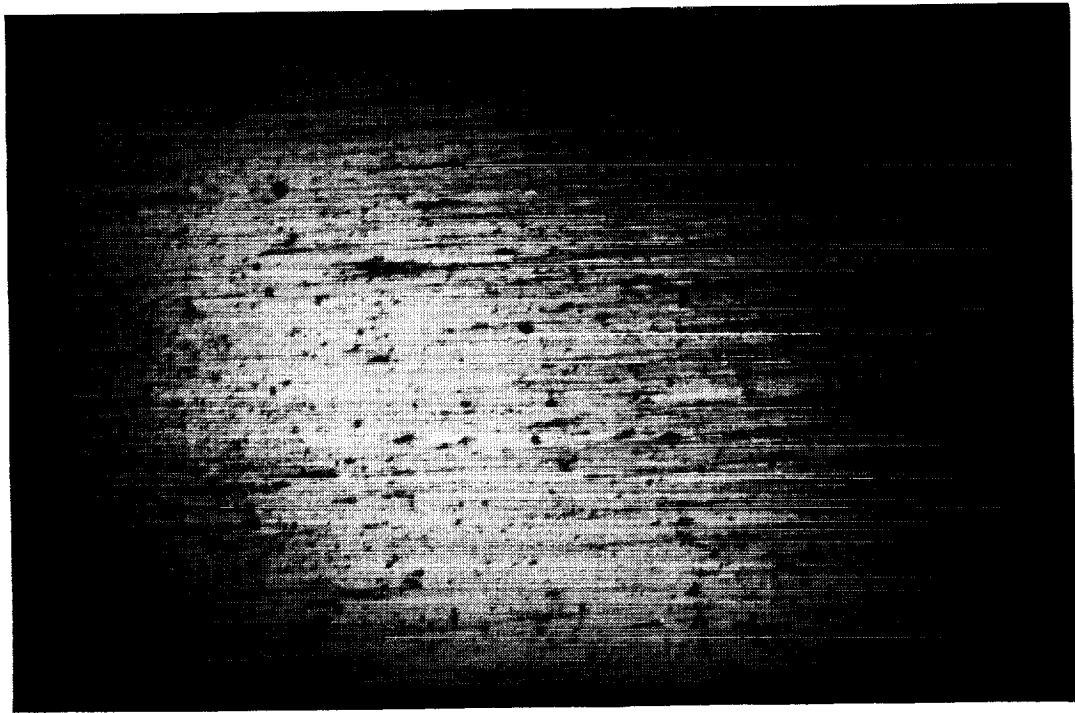


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AIRFOIL WITH LANGLEY-DEVELOPED CRYOGENIC HOT-FILM
ON UPPER SURFACE INSERT

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Throughout the transition detection studies in the 0.3-m TCT with the DAC cryogenic hot-film system (ref. 8), the on-line voltage output from various hot-film anemometers versus time traces on oscillographs and oscilloscopes showed a clear distinction between laminar, transitional, or turbulent boundary-layer states. However, on-line plots of the RMS voltages versus chordwise location (for an array of hot films) could not be obtained in real time due to numerous problems with the hot films and the data acquisition system. The results from a posttest analysis, which required the use of digitized data obtained from the FM tape recordings made during the test, clearly validated the ability of this type of system to detect boundary-layer transition at cryogenic conditions. However, it was also apparent from the tests that if this type of cryogenic hot-film system was to be used for the on-line detection of boundary-layer transition in the NTF, significant advances had to be made: (1) in the hot-film metalization process, (2) in the on-line data acquisition systems, and (3) in the type of dielectric that was used on the wings of large NTF models.

Since the transition detection study in the 0.3-m TCT (ref. 8), Langley has developed a new technique for a cryogenic hot-film metalization process, which includes a new type of dielectric substrate (ref. 9 and fig. 6). In addition, the simultaneous hot-film data acquisition system used in the 0.3-m TCT test was significantly enhanced (ref. 9). In order to evaluate both the new Langley hot-film deposition technique and the enhanced data acquisition system a low speed wind tunnel test was conducted with a model of the NACA 0012 airfoil. One surface of the 12 inch chord (12 inch span) had a chordwise array of 30 of the Langley hot films (fig. 7). The model also had a chordwise installation of 23 pressure orifices on the surface that also contained the 30 hot films.

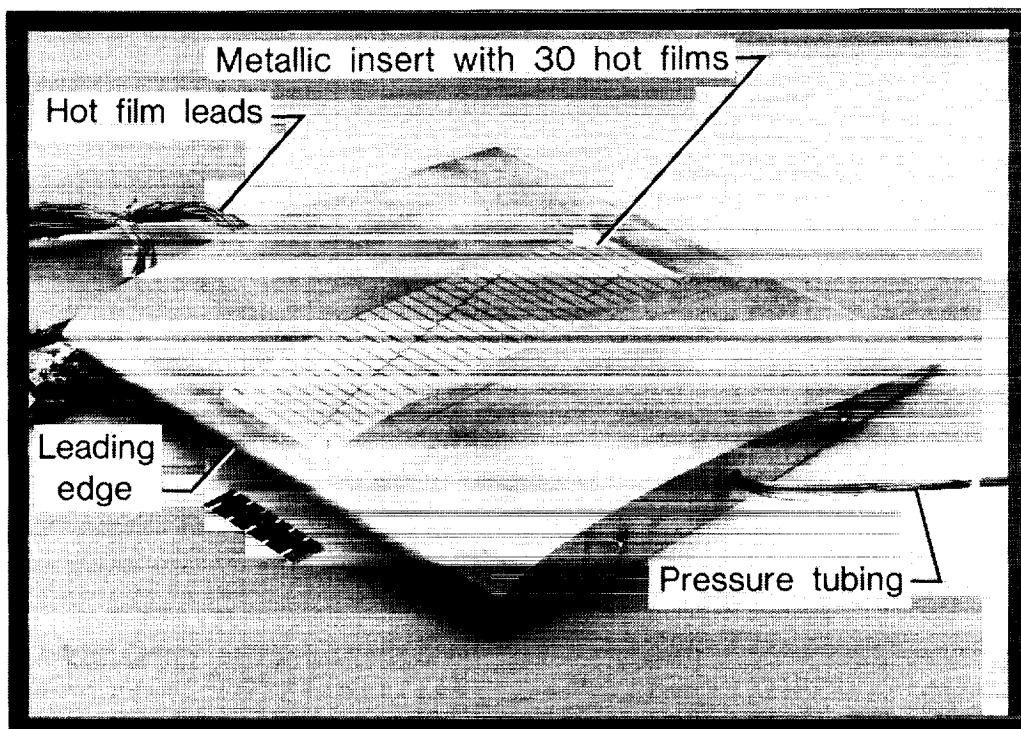


Figure 7

METALLIC INSERT USED IN AIRFOIL TEST OF CRYOGENIC HOT-FILM SYSTEM

The model used for the low-speed tests of the Langley cryogenic hot-film system, shown in figure 7, was fabricated with an internal core of high strength, closed-cell foam insulation and an outer shell of reinforced fiberglass. The stainless steel pressure tubing (0.20 in. i.d. and 0.30 o.d.) was routed through the internal core and was hand sanded to be flush to the fiberglass surface of the airfoil. A slot was cut in the upper surface of the airfoil for a 3 in. by 10 in. aluminum insert with a thickness of 0.125 in. on which 30 of the Langley developed cryogenic hot films were deposited.

The 3 by 10 inch aluminum insert (fig. 8) was closely fitted to the slot (i.e., no gaps) in the upper surface of the model and worked to conform to the design contour of the airfoil. Screws which fit into four countersunk holes in the corners of the insert held the insert in place so that the entire upper surface of the airfoil had the correct airfoil contour. There were 31 contact points (i.e., wire penetrations) on each side of the insert flush to the insert's outer surface.

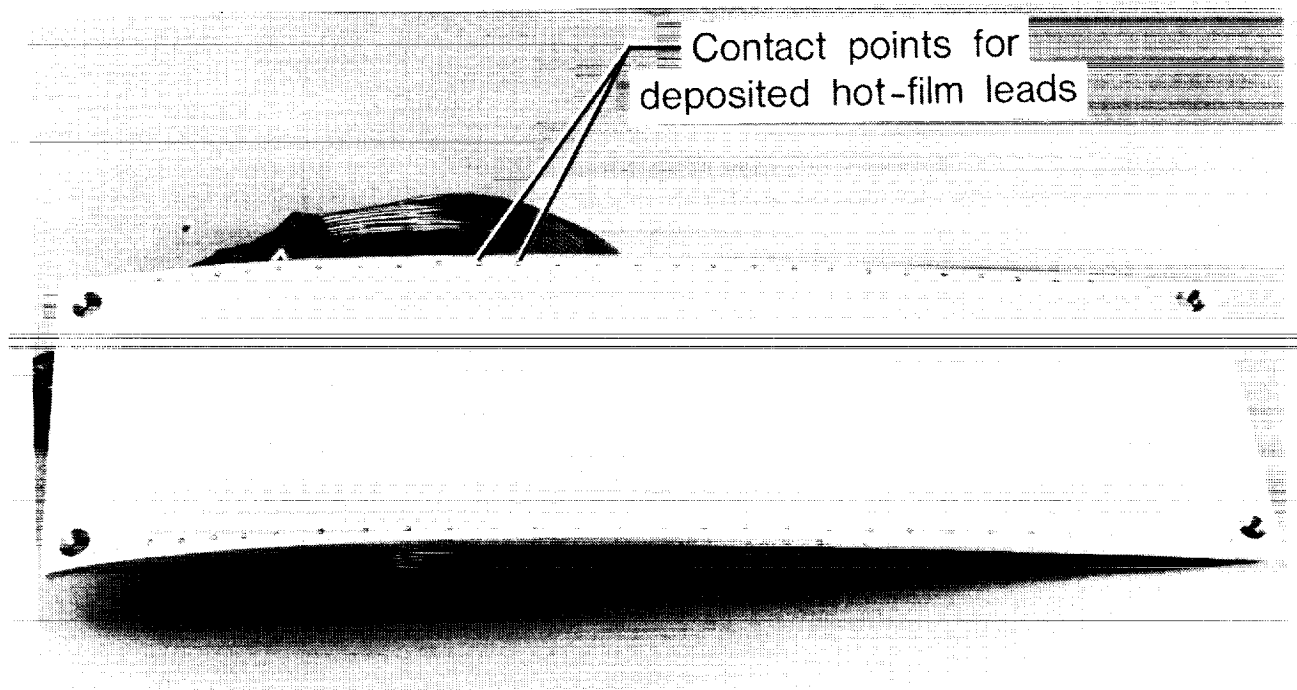


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BACKSIDE OF METALLIC INSERT USED FOR CRYOGENIC HOT-FILM INSTALLATION

The surface electrical wire penetrations (sometimes referred to as pin connections in 3-D model installations), shown in figures 4 and 7, must be installed in a manner that does not introduce a surface roughness which could trip the laminar boundary layer in a localized area. The backside of the aluminum insert (fig. 9), used for the 30 hot films, shows the epoxy compound used to bond the individual copper wire to the backside of the insert to ensure the wire penetrations remain flush to the surface of the insert. For the low speed tests (ref. 9), which were made at a constant ambient temperature, dissimilar metal for the model insert and wire penetrations (i.e., aluminum and copper) were used and presented no problem because of the near isothermal condition of the model during the test. However, for the wire surface penetrations used for cryogenic testing, the wires (or pins) must be of the same material to avoid a differential growth between the model and the pins when the model temperature varies from ambient condition to cryogenic condition.

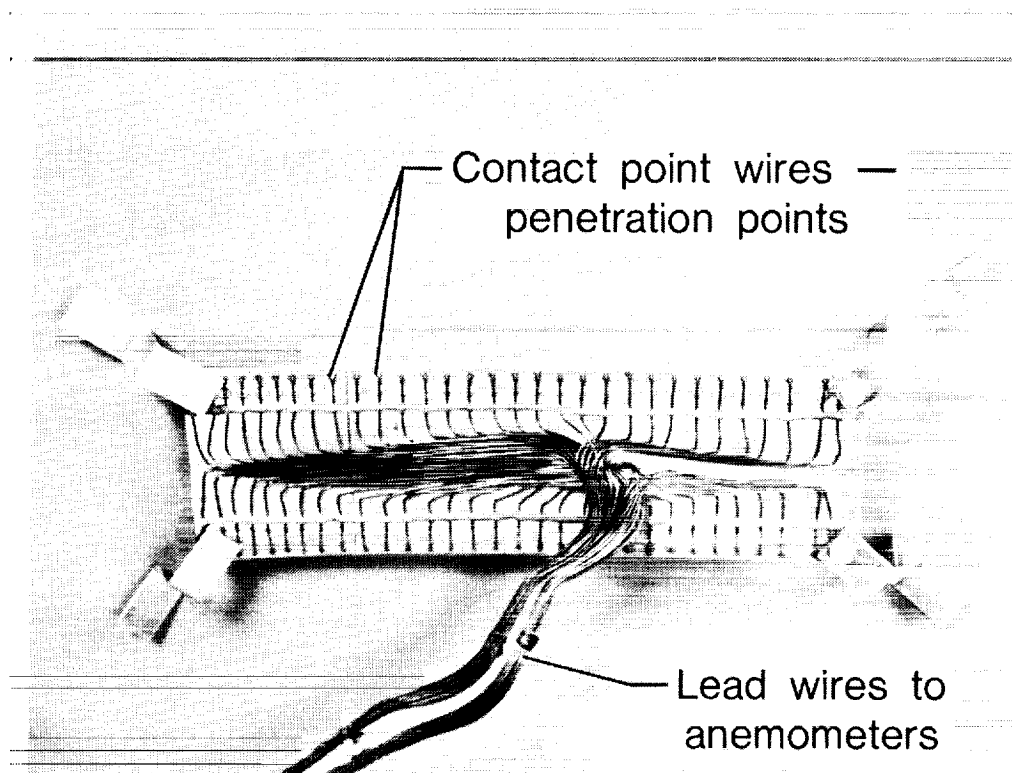


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METALLIC INSERT WITH CRYOGENIC SENSORS INSTALLED FOR LOW SPEED WIND TUNNEL TEST

Once the aluminum insert shown in figures 8 and 9 had been coated with Parylene C and SiO_2 , the contact points were cleared of any material that would impede the necessary secure electrical connection without exposing any of the surface of the aluminum insert to the vapor deposited aluminum leads. Next, the array of 30 hot films was vapor deposited on the insert by using a mask fabricated by a photolithographic technique. The array of 30 hot films and the 60 surface contact points were then connected by vapor deposited aluminum electrical leads (fig. 10).

The hot films were deposited in two swept arrays (skewed 15° from the model chord line), with 23 films in the array near the leading edge and the remaining 7 hot films in the downstream array. The 15° skew reduces the concentration of energy into the boundary layer along a given chord line that an unskewed array of films would produce. In addition, the skew reduces the downstream influence that a spurious turbulent wedge from a given hot film might have on the array of hot films. There is a shorted lead at the downstream end of the insert which is used to balance out any variation in lead resistance due to temperature changes, which will be an important consideration in testing in a cryogenic wind tunnel.

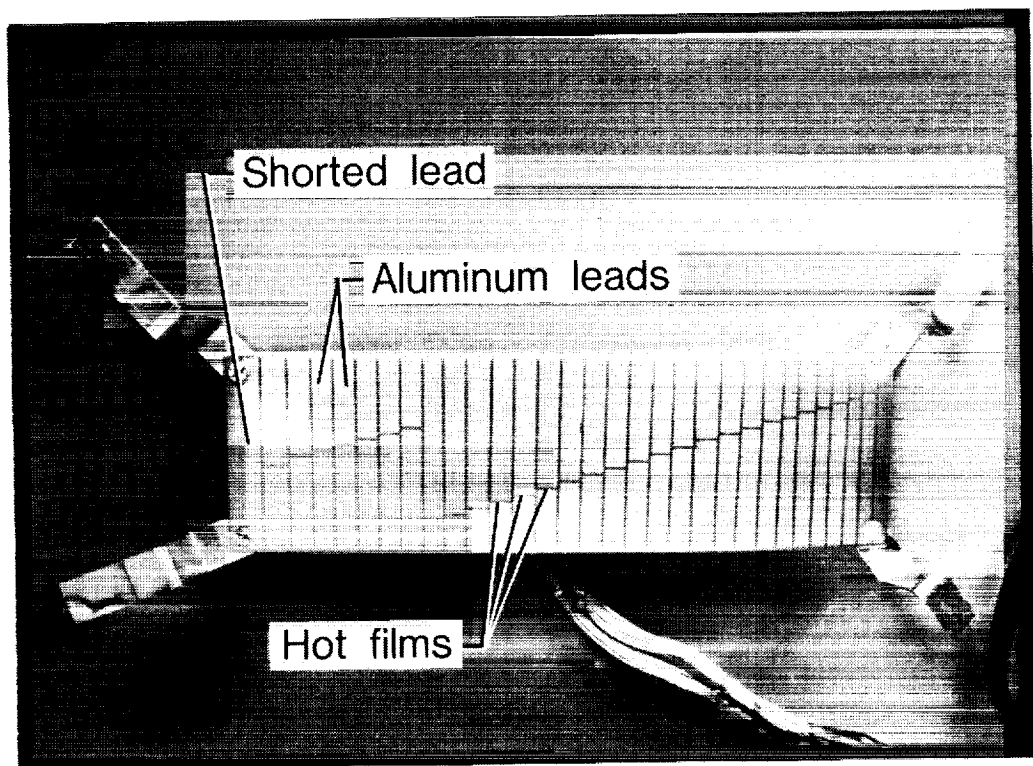


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CLOSEUP OF HOT-FILM INSERT INSTALLED IN AIRFOIL

An enlarged view of the forward portion of the NACA 0012 airfoil shows the upstream end of the hot-film insert installed in the upper surface (fig. 11). The hot films can be seen between the aluminum leads, and the electrical contact points can be seen at the chordwise edges of the insert. In addition, several of the pressure orifices can be seen in the lower right hand portion of the photograph.

The upstream end of the 10 in. long hot-film insert was located 0.4 in. from the leading edge of the airfoil, as measured along the chord line of the symmetrical airfoil. The chordwise centerline of the metallic insert was 5.5 in. from the right side of the model. The row of pressure orifices was 7.6 in. from the right side of the model. The model coordinates were within ± 0.001 in. of the design coordinate of the NACA 0012 airfoil.

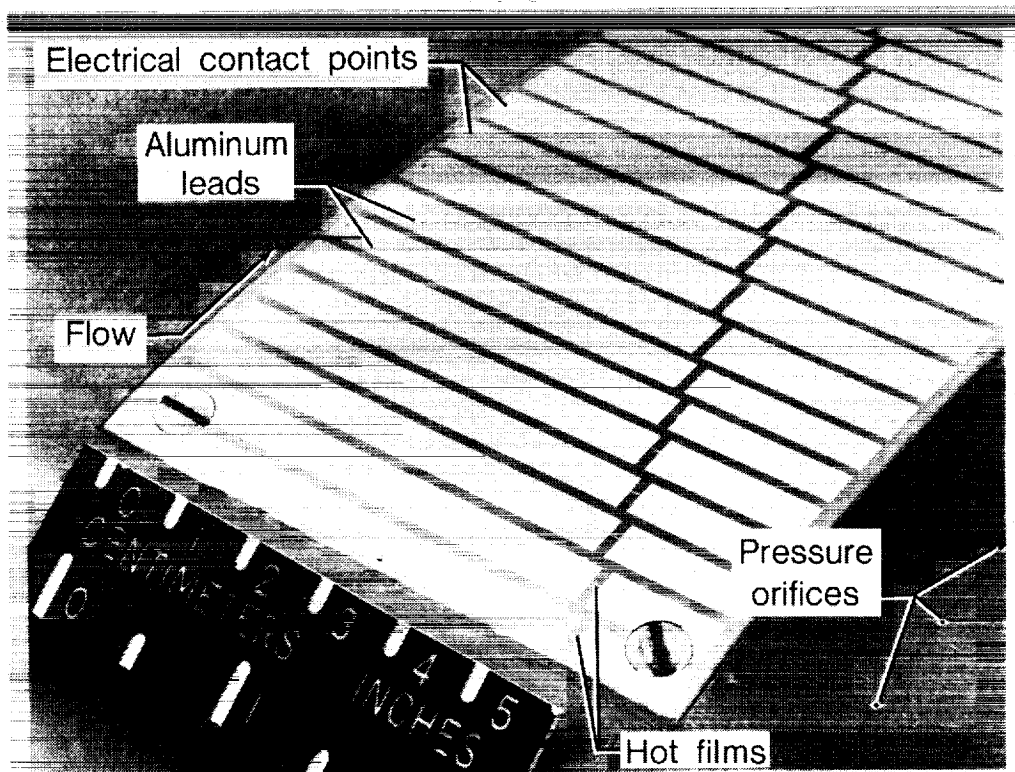


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INSTRUMENTED AIRFOIL MOUNTED IN LANGLEY SMALL CALIBRATION FACILITY

The instrumented NACA 0012 airfoil was tested in Langley's Instrument Research Division (IRD) small calibration facility (ref. 9). The facility is an open-circuit tunnel that takes in room temperature air, at ambient pressure, from within the building where the facility is located and exhausts the air in the same area of the building. The tunnel operates over a test section speed range from very low subsonic to a Mach number of about 0.25 and is driven by a 50 hp motor that operates a squirrel cage blower at either 885 revolutions per min (RPM) or 1780 RPM. At a given fan RPM, the tunnel speed is set by regulating 12 radial damper vanes which are located at the downstream end of the diffuser.

The airfoil was tested in a vertical position in the 17 in. by 12 in. test section with a chord line (at $\alpha = 0^\circ$) at the center of the floor and ceiling (fig. 12). The 12-in. span model was secured between two turntables located in the longitudinal center of the test section floor and ceiling. The angle of attack was set by the alignment of a finely marked circular scale on the top turntable to a finely scribed line on top of the test section that marked the longitudinal flow axis. The model was tested at angles of attack of -2° , 0° , and $+2^\circ$; at Mach numbers of 0.092, 0.122, and 0.247; and at chord Reynolds numbers of 0.65×10^6 , 0.86×10^6 , and 1.70×10^6 .

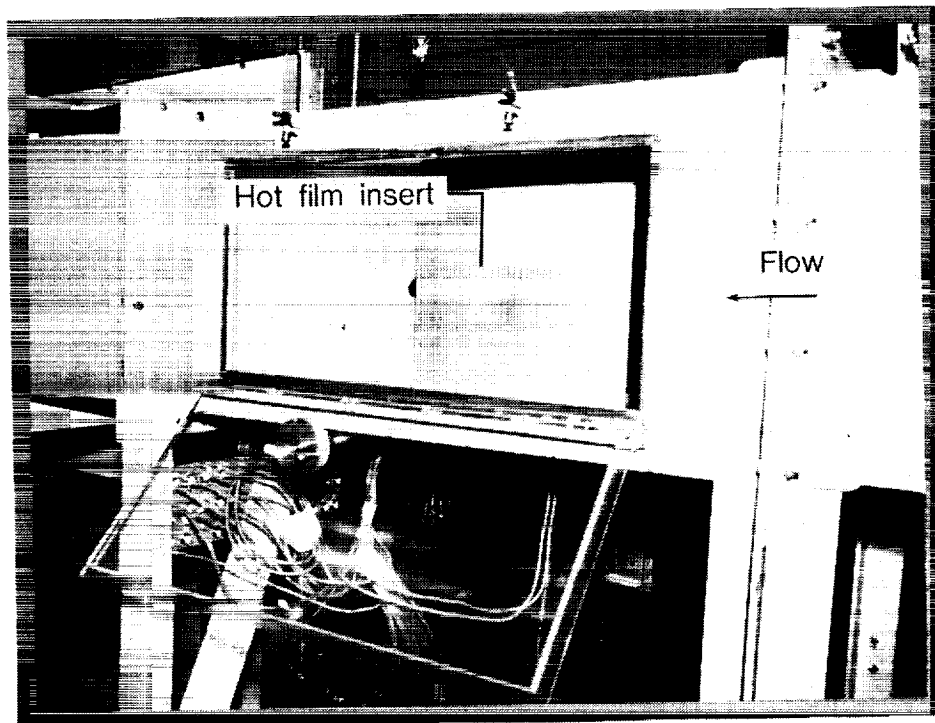


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ON-LINE CHORDWISE FLUCTUATING VOLTAGES FOR VARIOUS ANGLES OF ATTACK

One of the goals of the low-speed wind tunnel tests, with the hot-film instrumented NACA 0012 airfoil described with figure 12, was to demonstrate an on-line capability to obtain the location of the beginning and end of transition with a "specialized" cryogenic hot-film system (ref. 9). On-line transition data, presented as the ratio of the RMS voltage to the mean voltage across the anemometer bridge, were obtained for the chordwise array of hot films at a Mach number of 0.122 and chord Reynolds number of 0.86×10^6 at angles of attack of 0° and $\pm 2^\circ$ (fig. 13). The data indicate three distinct regions where the boundary layer is first laminar, then transitional, and finally fully turbulent. The transitional region is between the beginning and end of transition. The sudden rise in the normalized voltage indicates the beginning of transition. In the transition region the normalized voltage reaches a peak value and then rapidly decreases to a point where the voltage has a nearly constant value which indicates the end of transition. The normalized voltage for the laminar boundary layer upstream of the beginning of transition has a value slightly less than 0.1 while the normalized voltage for the fully turbulent boundary layer downstream of the end transition has a value between about 0.5 and 0.8. As the angle of attack increases from -2° to 0° to $+2^\circ$, the location of the beginning of transition correspondingly moves forward from 51 to 43 to 24 percent of chord. This forward movement of the beginning of transition is expected based on the type of pressure gradients noted in the pressure distribution which were obtained during the test program (ref. 9).

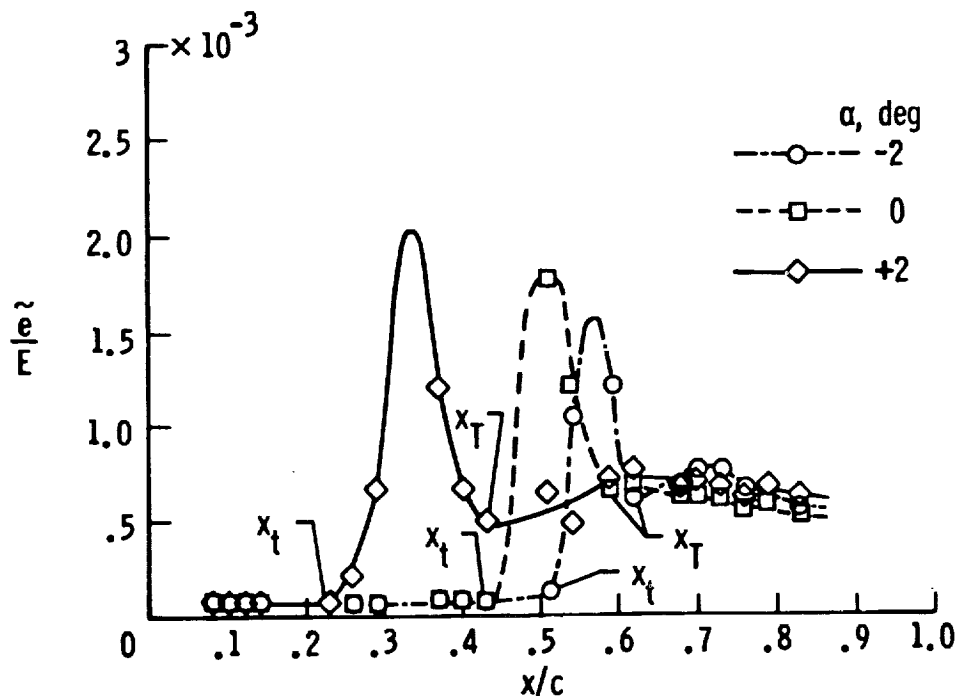


Figure 13

ON-LINE CHORDWISE FLUCTUATING VOLTAGES FOR VARIOUS MACH NUMBERS

On-line normalized fluctuating voltages, which indicated the beginning and end of transition, were also obtained from the chordwise array of hot films for Mach numbers of 0.092, 0.122, and 0.247 at an angle of attack of 0° (fig. 14). The RMS fluctuating voltages for the three Mach numbers again indicate the beginning and end of transition based on the sharp increase and rapid decrease of normalized voltages in the region where the boundary layer is transitional. When the Mach number increased from 0.092 to 0.122, there was a slight forward movement in the voltage distribution that defined the transitional region, but a clear difference in the beginning and end of transition could not be distinguished because of variations in the spacing of the operational films in the array. For the two lowest Mach numbers the beginning and end of transition appears to be 43 and 59 percent, respectively. When the Mach number was increased to 0.247, there was a significant upstream movement in the location of the beginning of transition to about 10 percent of chord. In addition, the chordwise extent of the transition region more than doubled and the level of the normalized voltage for the fully turbulent boundary in was 60 to 70 percent higher than the normalized voltage for the two lower Mach numbers.

Thus, fluctuating voltage obtained in a real-time mode from a closely spaced chordwise array of hot films (figs. 13 and 14) will give a clear indication of the beginning and end of transition with the new Langley hot films and an enhanced simultaneous data acquisition system.

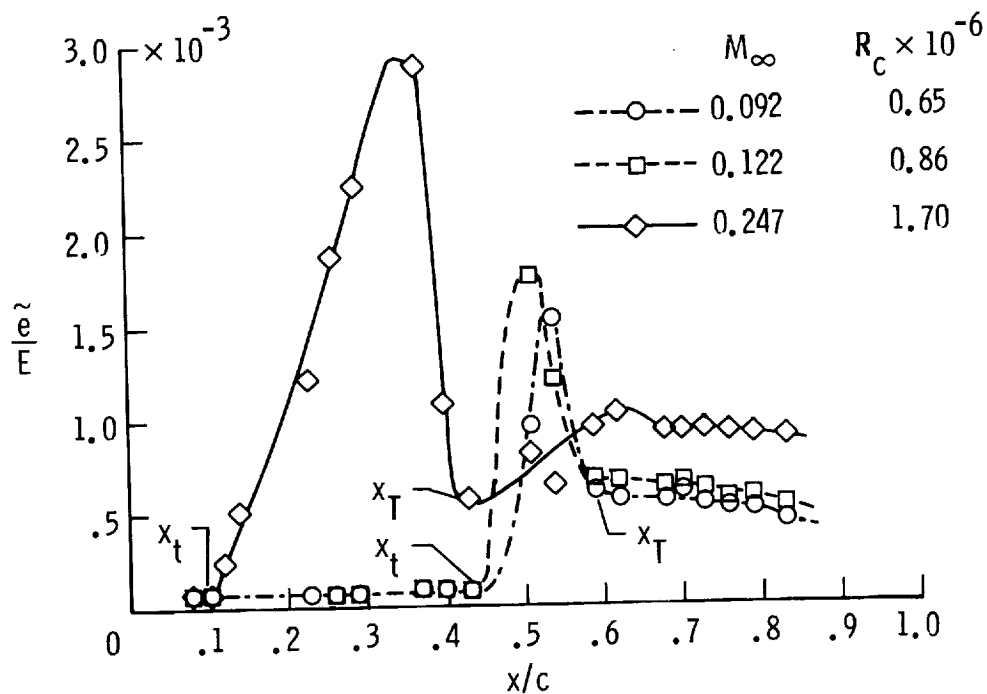


Figure 14

FLUCTUATING CHORDWISE VOLTAGES AND CORRESPONDING VOLTAGE VERSUS TIME TRACES

The fluctuating voltage output from the hot films, which was recorded on FM tape with a 28 track tape recorder (ref. 9), was examined on oscilloscopes both during (i.e., on-line) and after the tests. From the posttest examinations, selected voltage-versus-time traces, that correspond to RMS voltages in figures 13 and 14, were obtained with a digital storage oscilloscope and were then plotted directly on an analog x-y plotter (ref. 9). The voltage-versus-time traces (fig. 15), which correspond to specific values of RMS voltage, at an angle of attack of 0° , a Mach number of 0.122, and a chord Reynolds number of 0.86×10^6 , clearly indicate the waveform for a laminar boundary layer associated with the low RMS voltages upstream of the beginning of transition. Downstream of the end of transition the waveform is that of a fully developed turbulent boundary with the associated elevated level of RMS voltage. The transition region, between the beginning and end of transition, indicates the expected positive voltage spikes caused by turbulent bursts in the area where the RMS voltage is increasing and also indicates the negative voltage spikes associated with "laminar intervals" in the area where the RMS voltage is decreasing. The voltage versus time traces (fig. 15) are typical of those from tests with similar cryogenic hot films systems (ref. 9) and from tests with conventional hot films systems (ref. 3).

The data acquisition system which enabled the realization of on-line transition detection consisted of 30 channels of hot-film anemometry, a computer-controlled switching network, scanner, digital multimeter, filter, and true RMS meter. All components in the system were calibrated very carefully to ensure that each channel of hot-film anemometry would have a nearly uniform sensitivity and frequency response. Measurements were directly taken with the digital multimeter and assimilated in the desktop computer. They were then displayed as a plot of e/E vs x/c .

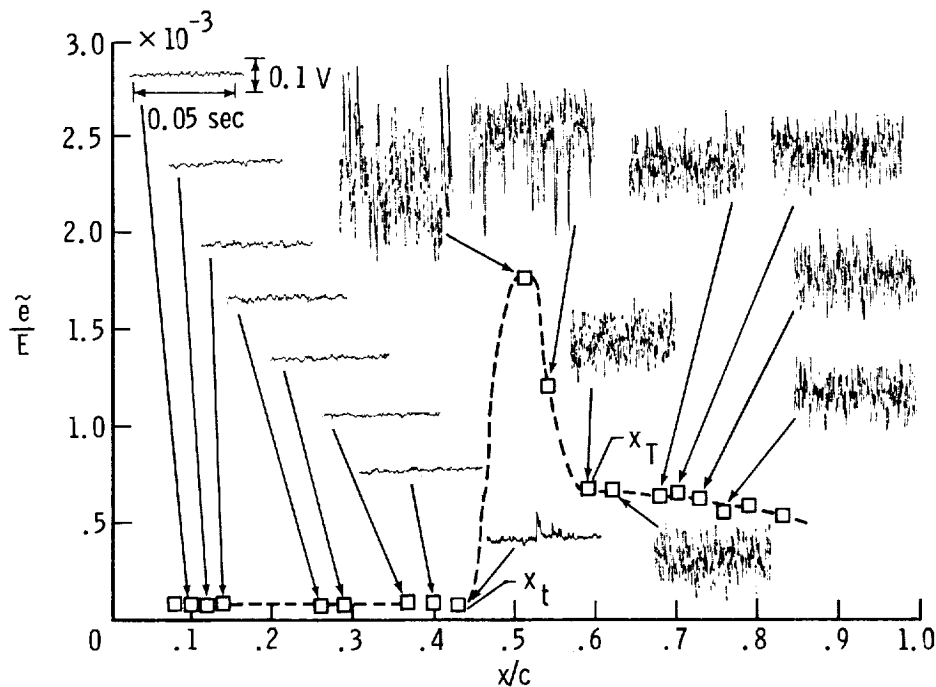


Figure 15

TEST OF CRYOGENIC HOT-FILM DIELECTRIC WITH AIRFOIL MOUNTED ON TEST SECTION SIDEWALL OF NTF

Two test entries were made in the NTF to evaluate the durability and survivability of the Parylene C dielectric substrate over a wide range of Mach numbers, Reynolds numbers, and total temperatures. Each facility entry was about 2 weeks in duration and remained in the test section during the entire "primary" test program. The two qualitative evaluation tests were made with an 8-in. span, 5.575-in. chord, 20-percent thick symmetrical airfoil and were mounted on the side wall of the test section of the NTF (fig. 16). Two separate, but identical, airfoil sections with a 0.0003-in. thick coating of Parylene C were used in each of the tunnel entries. The airfoil sections were mounted on the right side wall of the test section well downstream of the primary force and moment model. During both tests, a minimum of 4 inches of the outboard portion of the coated airfoil was in the freestream flow of the test section, and at highest Reynolds numbers as much as 7 inches of the airfoil span were in the free stream. During the first entry, the NTF was operated in the air mode at Mach numbers from 0.2 to 0.9, a total temperature of 100°F, and a total pressure of about 1 atm. A posttest examination of the Parylene C coating indicated no mechanical failure and an electrical check indicated the coating would be an excellent dielectric substrate for the hot-film system. During the second tunnel entry, a second airfoil, also coated with 0.0003 in. of Parylene C, was tested in the cryogenic mode. During the tests, the Mach number varied from low subsonic to 1.15, and the total temperature was as low as -247°F (118 K), with a dynamic pressure as high as 3600 PSF. These test conditions represented a severe set of test conditions for the Parylene C dielectric. The results of a posttest examination again indicated no mechanical failure of the dielectric substrate at the high dynamic pressure - cryogenic condition. An electrical check again indicated the Parylene C would serve as an excellent dielectric substrate for the cryogenic hot-films system.

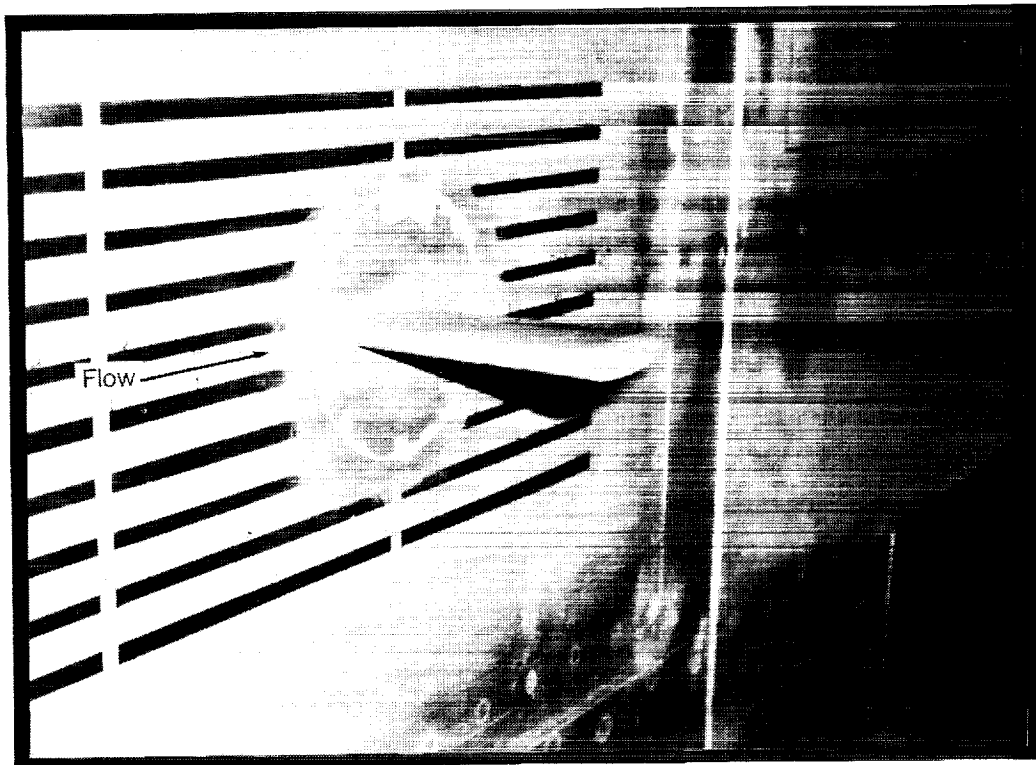


Figure 16

**DAC - NTF PATHFINDER I WING WITH PROVISIONS FOR THE
INSTALLATION OF CRYOGENIC HOT FILMS**

The application of the cryogenic hot-film system to three-dimensional models is the next step in the development of this measurement technique. It is well known that future test programs of airplane configurations in the NTF all have the general user requirement of a boundary-layer transition detection capability, preferably on-line. At this time, the only cryogenically validated transition detection system is the vapor deposited hot-film system as discussed in this section of the publication. Currently there are NTF models, in the general class of transport aircraft, that contain the necessary surface pin penetrations on the surface to accommodate the installation of the Langley cryogenic hot films. One of these NTF models is the Douglas Aircraft Company's (DAC) Pathfinder I wing (fig. 17) which has 44 surface penetrations pins installed at 4 spanwise stations (i.e., four chordwise arrays of hot films) on the upper surface of the right hand span of the wing. The installation technique that DAC has developed for hot-film pin penetration produces an extremely smooth surface at the point of penetration. The pins for the hot-film leads are electrically isolated from the model and are attached to lead wires that connect to the hot-film data acquisition system.

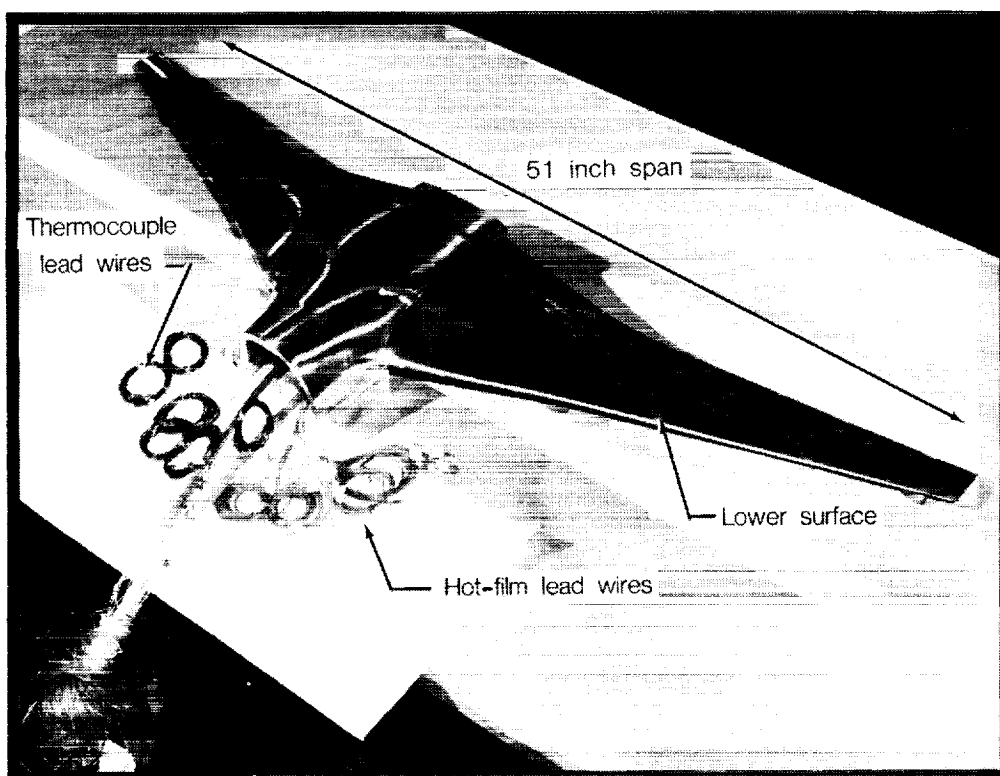


Figure 17

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VACUUM CHAMBERS AT LANGLEY FOR DEPOSITION OF CRYOGENIC HOT FILMS ON LARGE MODELS

Since there has been a requirement for transition detection on NASA models to be tested in the NTF for a number of years, coupled with the DAC requirement that a cryogenic hot-film system be vapor deposited on the 51-inch span wing, shown in figure 17, Langley has been developing a large-scale deposition system. The large scale system will consist of two large vacuum chambers (5 ft i.d.) and the required large capacity vacuum system to go with both chambers (fig. 18). The two large chambers were obtained from surplus equipment and are being refurbished for use as large vacuum chambers.

One of the large chambers (fig. 18) will be used to deposit the Parylene C dielectric substrate on the large wings of NTF models and will have a Parylene C system similar to Langley's small scale system (ref. 9). The other large chamber (fig. 18), for the metalization/deposition process, is made from stainless steel and will require a much lower vacuum than the chamber used for the dielectric. The system for the large metalization/deposition chamber will be similar to Langley's small scale system (ref. 9). In addition, two large 30 horse power mechanical vacuum pumps with a pumping capacity of 730 CFM were also obtained from surplus. One of the mechanical pumps will provide a sufficiently low vacuum for the chamber used for dielectric deposition. The other vacuum pump will serve as the roughing pump for the large metalization/deposition chamber which requires a much lower pressure (i.e., 10^{-5} to 10^{-6} mm of mercury). A diffusion pump will be used in the vacuum system for this chamber to obtain the necessary high vacuum required for metalization/deposition.

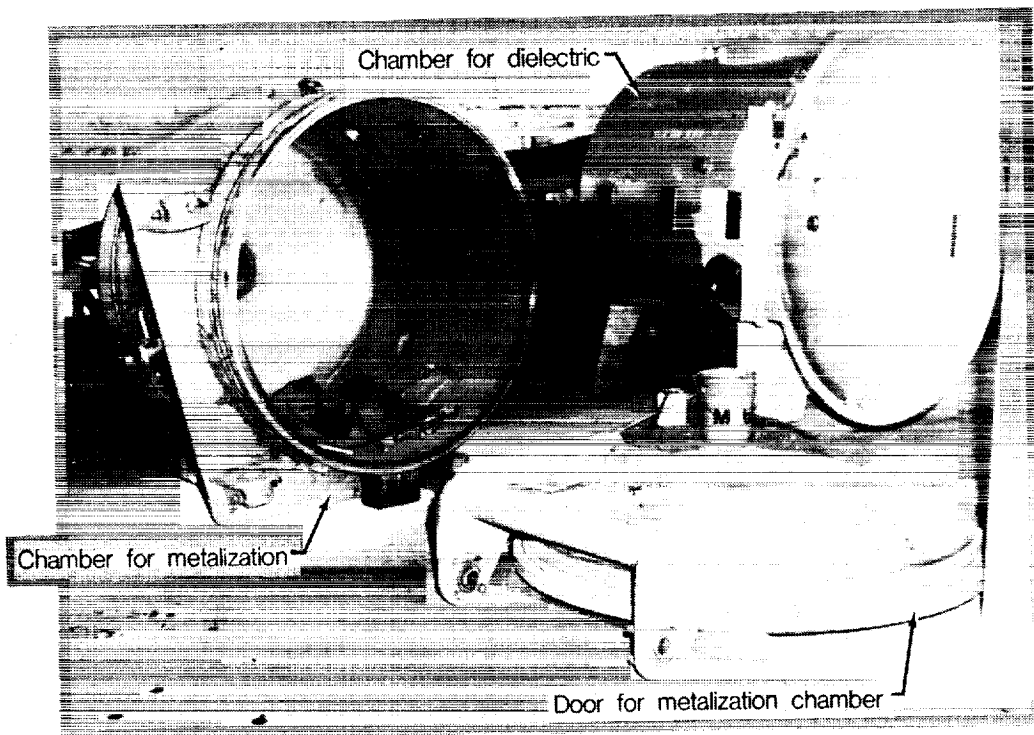


Figure 18

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